

# Tevatron measurements on Standard Model Higgs

49<sup>th</sup> Rencontres de Moriond  
Electroweak Interactions and Unified Theories

Federico Sforza  
on behalf of the CDF and D0 Collaborations

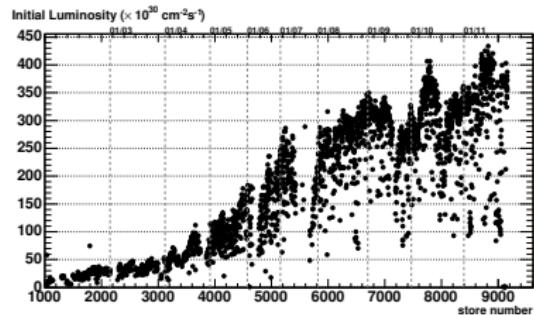
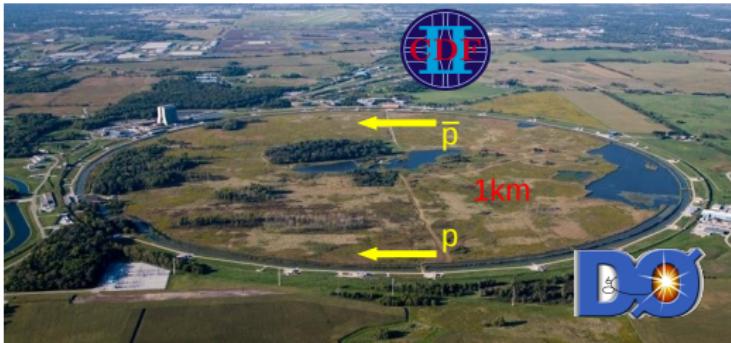
Max Planck Institut für Physik

20<sup>th</sup> March 2014 - La Thuile

# The Tevatron

Presented analyses use full Run II dataset:

Up to  $\int \mathcal{L} \simeq 10 \text{ fb}^{-1}$  of  $p\bar{p}$  collisions at  $\sqrt{s} = 1.96 \text{ TeV}$  per experiment ( $\simeq 12 \text{ fb}^{-1}$  delivered)

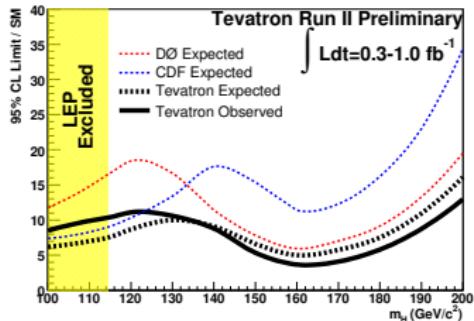


Store initial luminosity  $\times 20$  increase over years  
 $\Rightarrow$  driven by abundance of anti-protons

## Tevatron facts:

- Two instrumented collision points: **CDF & D0** experiments
- First superconducting accelerator and largest *anti-matter* source in the world
- Run I and Run II cover almost 20 years of physics

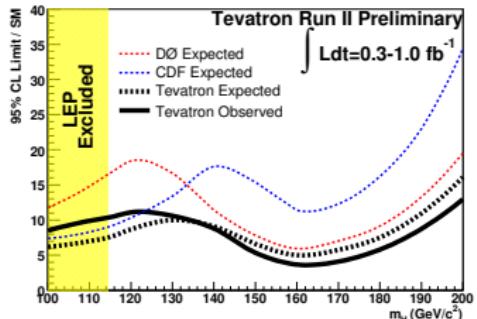
# A Very Brief History of Higgs Searches



Tevatron role was unexpected several years ago:

- First Tevatron combination for SM Higgs 95% C.L.:  
 $\Rightarrow 2006, 0.3 - 1 \text{ fb}^{-1}$  ([CDF 8384 & D0 5227 Notes](#))
- 95% exclusion sensitivity  $\mathcal{O}(10) \times \text{SM}$
- $100 \text{ fb}^{-1}$  needed to reach  $2\sigma$  sensitivity!

# A Very Brief History of Higgs Searches

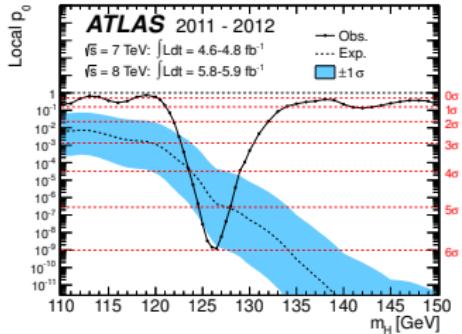


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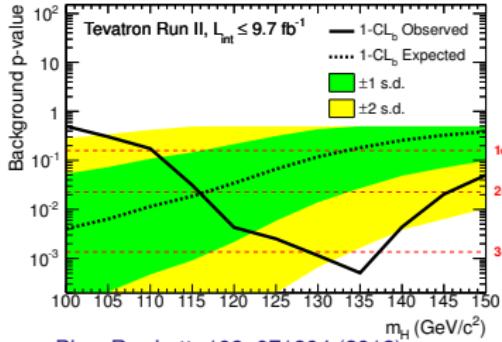
The July 2012 discovery of a new particle compatible with SM Higgs ( $m_H \approx 125 \text{ GeV}/c^2$ ):

ATLAS, CMS observation in  $4\ell, \gamma\gamma$  final states:



Phys. Lett. B 716 (2012) 1 and 30

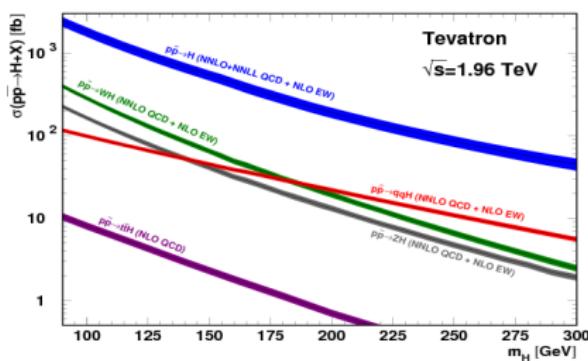
Tevatron evidence in  $b\bar{b}$  final state:



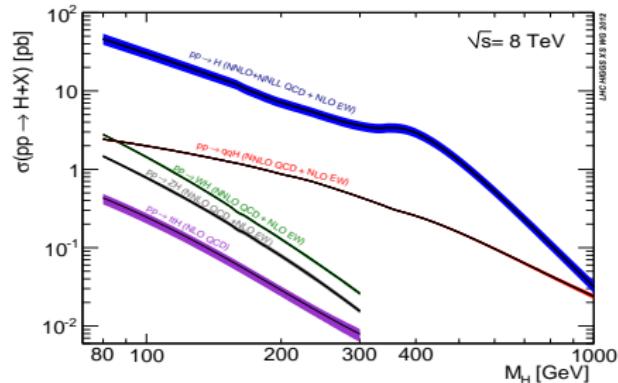
Phys. Rev. Lett. 109, 071804 (2012)

# Higgs Production Mode Differences at Tevatron and LHC

Tevatron Higgs production modes (1.96 TeV):

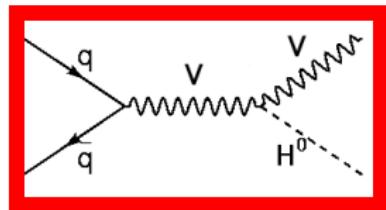


LHC Higgs production modes (8 TeV):

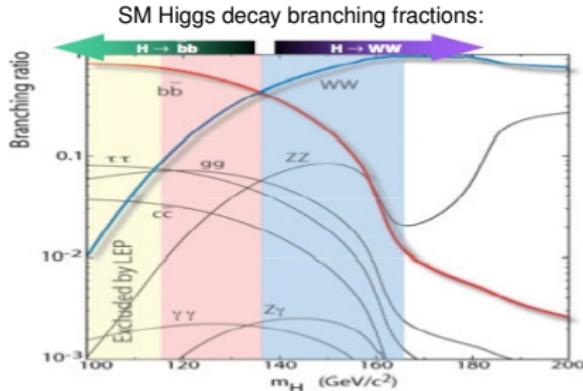


Higgs production rate at LHC much higher than at Tevatron:

- LHC gluon fusion  $\times 20$ , Vector Boson Fusion (VBF)  $\times 30$ 
  - $\Rightarrow$  Abundant production modes for analysis of clean final states with small BR ( $\gamma\gamma$ ,  $ZZ$ ,  $WW$ ,  $\tau\tau$ )
- LHC  $VH$  associate production  $\times 4$ , also higher background:
  - $\Rightarrow$  *Relevant and complementary studies from Tevatron!*



# Analysis Classification



## High Mass:

- High BR final states for  $m_H \gtrsim 135 \text{ GeV}/c^2$
- Main channel:  $gg \rightarrow H \rightarrow WW$
- $WW \rightarrow \ell\nu\ell\nu$ : low background
- High Higgs production rate

## Low Mass:

- High BR final states for  $m_H \lesssim 135 \text{ GeV}/c^2$
- main channel:  $qq \rightarrow VH \rightarrow b\bar{b}$
- V leptonic decay: online selection and background reduction

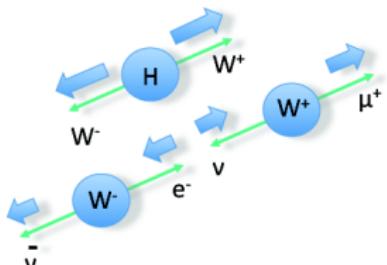
Peculiarity of  $m_H = 125 \text{ GeV}/c^2$ :  $BR(H \rightarrow b\bar{b}) \simeq 0.58$ ,  $BR(H \rightarrow WW) \simeq 0.21$

⇒ Both low and high mass analyses contribute to properties study

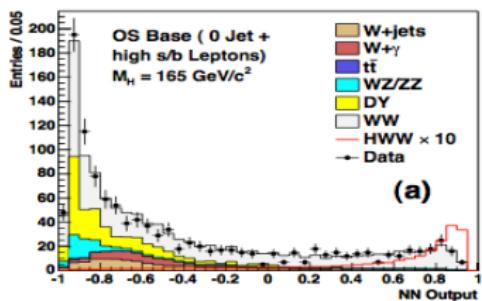
# Overview of $H \rightarrow WW$ Analysis

- Lepton plus  $E_T$  selection (also hadronic  $\tau$ ):  
 ⇒ *s/b* event categorization to enhance sensitivity
- Low Higgs mass resolution because of  $2\nu$
- Lepton kinematic correlation for MVA discriminants:  
 ⇒ Boosted Decision Trees (BDT), usually for D0  
 ⇒ Neural Networks (NN), usually for CDF

Different di-lepton kinematic of  $H \rightarrow WW$  decay and  $WW$  EWK production (background):

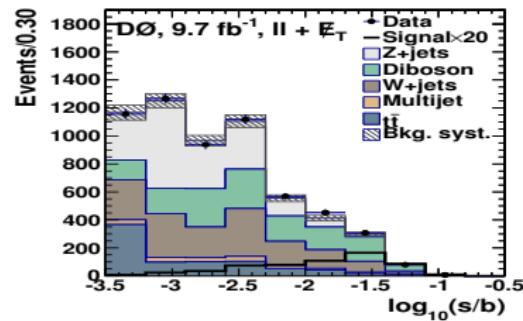


Example of CDF  $H \rightarrow WW$  NN output:



Phys. Rev. D 88, 052012 (2013)

Example of D0  $H \rightarrow WW$  BDT output:



Phys. Rev. D 88, 052006 (2013)

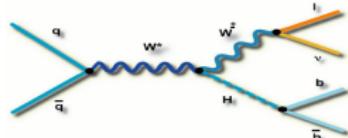
2008: first post LEP analysis to exclude presence SM Higgs boson in mass range

# Overview of Low Mass Higgs Analyses

$VH \rightarrow b\bar{b}$  is the most sensitive channel at Tevatron:

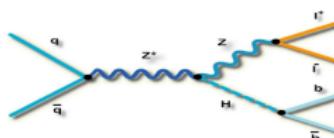
**3 analyses with similar topology: leptons (charged or neutral) + heavy flavor jets**

$$p\bar{p} \rightarrow WH \rightarrow \ell\nu + b\bar{b}$$



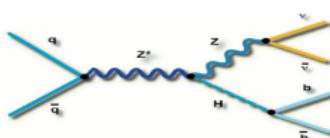
CDF: Phys.Rev.Lett. 109, 111804 (2012),  
 D0: Phys.Rev.Lett. 109, 121804 (2012),  
 Phys.Rev.D. 88, 052008 (2013)

$$p\bar{p} \rightarrow ZH \rightarrow \ell\ell + b\bar{b}$$



CDF: Phys.Rev.Lett. 109, 111803 (2012),  
 D0: Phys. Rev. Lett. 109, 121803 (2012),  
 Phys.Rev.D. 88, 052010 (2013)

$$p\bar{p} \rightarrow VH \rightarrow \nu\bar{\nu}(\nu\ell) + b\bar{b}$$



CDF: Phys.Rev.D 87, 052008 (2013),  
 D0: Phys.Lett.B 716, 285 (2012)

- Similar background sources, different relative fractions between final states
- Aim to identify Higgs  $M_{b\bar{b}}$  resonance over falling background
- Background estimate with mixture of MC/data driven extraction from Control Regions (CR)

Backgrounds	Shape	Normalization
$WW, WZ, ZZ, t\bar{t}$ , single-top	MC based	NLO,NNLO (Theory)
Multi-Jet (MJ)	Data driven	Fit to data
$W/Z +$ light flavor	MC (ALPGEN), CR weighted	data CR
$W/Z +$ heavy flavor	MC based (ALPGEN)	LO, fit to data

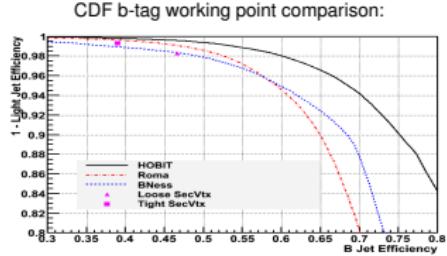
Statistically limited dataset  $\Rightarrow$  Relax cuts  $\Rightarrow$  Keep background under control  $\Rightarrow$  **Iterate**

# Low Mass Searches Optimization

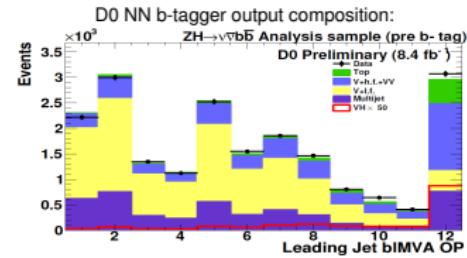
Every aspect of analyses thoroughly optimized (often using MVA):

- Inclusive trigger strategy: single lepton, only  $\cancel{E}_T$ , multiple objects ( $\cancel{E}_T + \text{jets}$ )
- Improved  $\ell/\cancel{E}_T$  offline ID: relaxed cuts increases MJ  $\Rightarrow$  improve lepton ID/MJ-rejection
- b-tag: reduce background to 1/100 but limits jet selection efficiency ( $\simeq 50\%$ )
- Final Discriminant: large irreducible backgrounds  $\Rightarrow$  MVA sensitivity increase by 10-20%

- MVA b-tagging for both D0 and CDF
- Tunable efficiency/contamination working point
- Maximize significance from  $s/b$  categorization of signal region

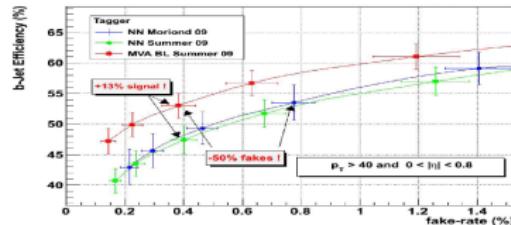


J. Freeman et al., Nucl.Instrum.Methods Phys.Res., Sect. A 697, 64 (2013)



V. M. Abazov et al., Nucl.Instrum.Methods Phys.Res., Sect. A 620, 490 (2010)

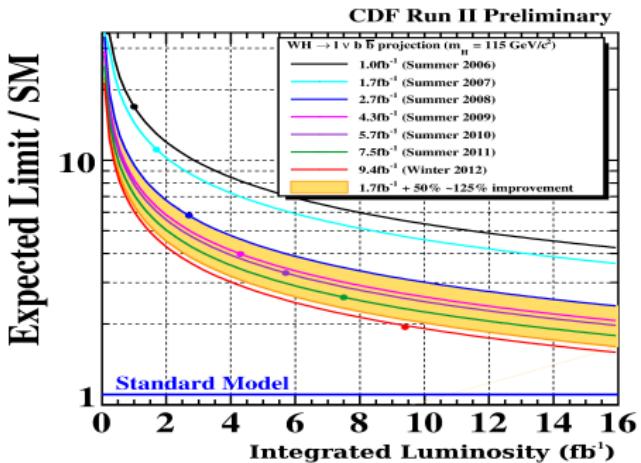
D0 b-tag algorithm improvements and working points:



# Low Mass Searches Optimization

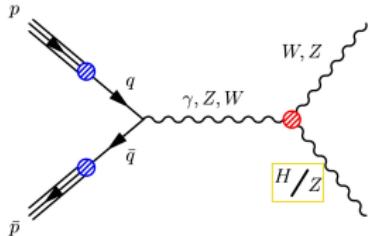
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Single channel sensitivity improvements w.r.t. 1 fb $^{-1}$  analysis was also > 200% (over luminosity)!

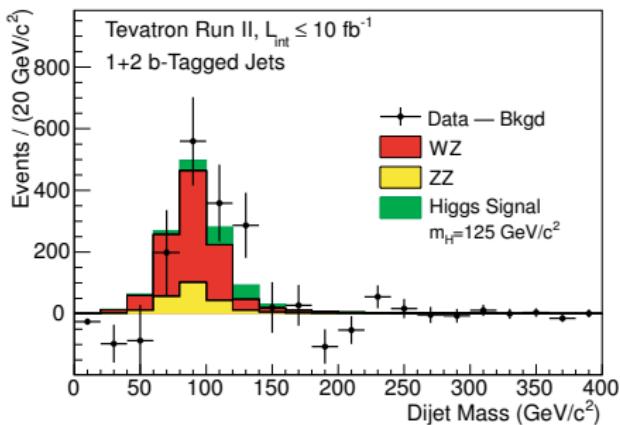
# Analysis Validation with $VZ \rightarrow HF$



- Important analysis validation using known SM process as signal
- $VZ$  associate production in  $s$ -channel with  $Z \rightarrow b\bar{b}$  mimics  $VH \rightarrow b\bar{b}$  signature
- $\sigma_{VZ} \times BR(Z \rightarrow HF)$  about 6 times  $VH$  ( $M_H = 125$ )
- Higher background due to  $W+jets$   $M_{jj}$  spectrum  
 $\Rightarrow$  very small  $s/b$  and challenging measurement!

## $WZ \rightarrow HF$ evidence

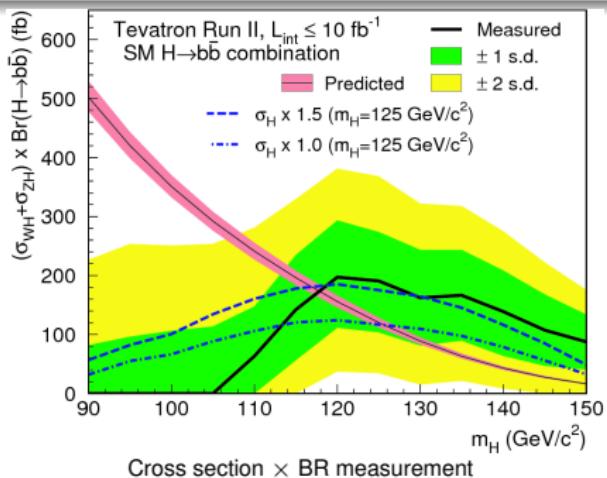
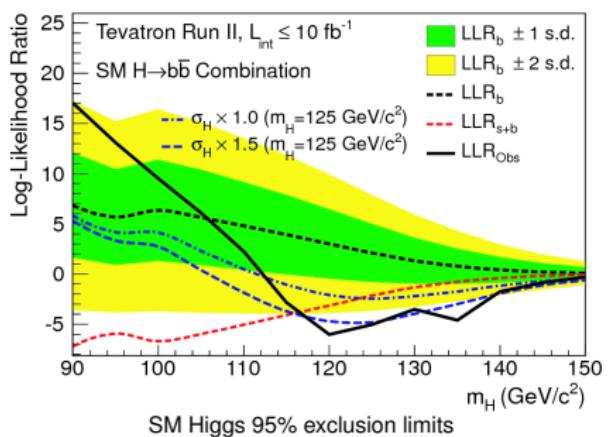
- CDF and D0 low mass analyses combined looking at  $VZ \rightarrow HF$  signal
  - Same data-set, analysis techniques, MVA discriminant strategy
- $\Rightarrow \sigma_{VZ} = 3.0 \pm 0.6(\text{stat}) \pm 0.7(\text{syst}) \text{ pb}$   
 $\Rightarrow$  Strong signal evidence at  $4.6 \sigma$   
 $\Rightarrow$  Consistent with  $\sigma_{VZ}^{SM, NLO} = 4.4 \pm 0.3 \text{ pb}$



Background subtracted di-jet invariant mass

# $H \rightarrow b\bar{b}$ Results

- Phys.Rev.Lett. 109, 071804 (2012):  $H \rightarrow b\bar{b}$  low mass  $VH$  Tevatron combination in 2012
- Phys.Rev.D 88, 052014 (2013): properties of  $H \rightarrow b\bar{b}$  from all channel update in July 2013



Significant excess over background only hypothesis:

- Analysis using both Log Likelihood Ratio (LLR) and Bayesian posterior cross section measurement
- $\sigma(WH + ZH) \times BR(H \rightarrow b\bar{b}) = 0.19 \pm 0.09 \text{ pb}$  (SM exp.  $0.12 \pm 0.01$ )  
 $\Rightarrow$  Measurement of  $H \rightarrow b\bar{b}$  competitive with LHC

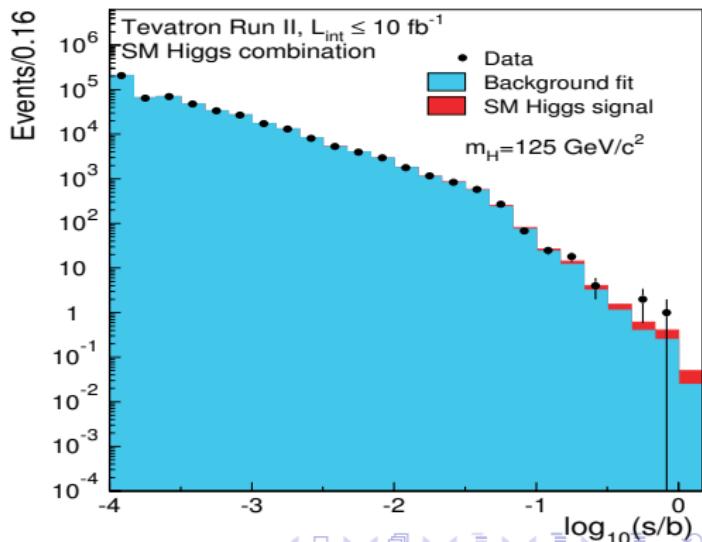
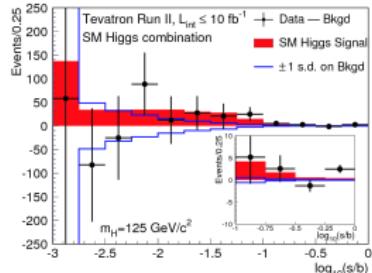
# Tevatron Combination for All Analysis Channels

Next step  $\Rightarrow$  analyze SM Higgs from combination of all analysis channels,  $> 100!$

- $H \rightarrow WW$  and  $H \rightarrow b\bar{b}$  are the most important, but also  $H \rightarrow \gamma\gamma$ ,  $H \rightarrow \tau\tau$
- SM Higgs hypothesis testing is possible only looking at all the predicted decay modes
- Measure parameter of new particle: [Summer 2013 Results](#)

The global picture:

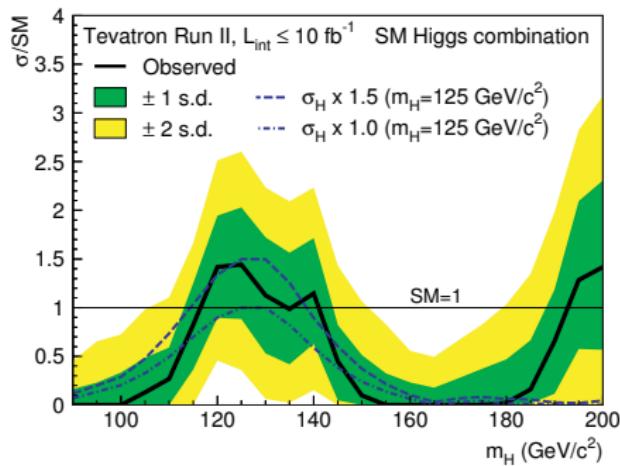
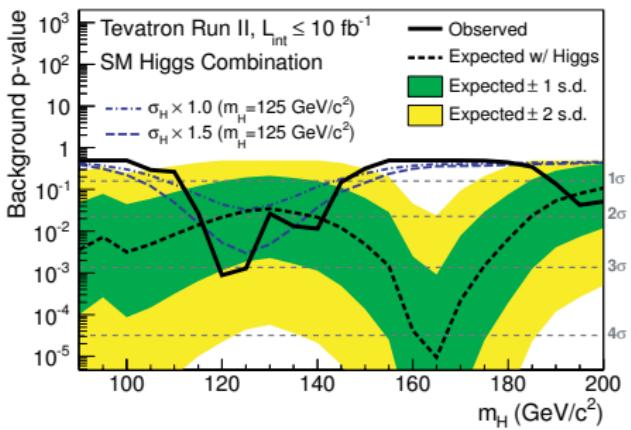
- Classification of all final discriminants in  $s/b$  bins
- Preserve importance of each data event
- $\log_{10}(s/b)$  shows agreement over 5 orders of magnitude



# $p$ – values and Cross Section

The full Tevatron combination results:

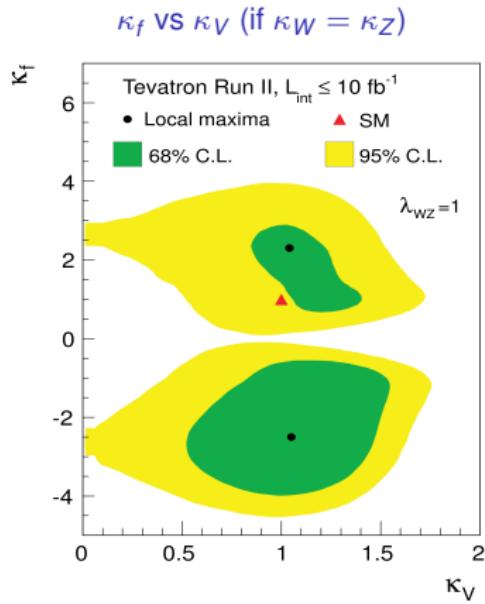
- Analysis of each channel discriminant with combined likelihood
- $p$ -value  $3.0\sigma$  (local) at  $m_H = 125 \text{ GeV}/c^2$  (1.9 expected)
- $\mu = \sigma_{obs}/\sigma_{SM} = 1.44^{+0.59}_{-0.56}$  at  $m_H = 125 \text{ GeV}/c^2$
- Consistent cross section between channels and with SM expectation



# Higgs Coupling Measurements

- Most sensitive Higgs production and decay modes via  $W$ ,  $Z$ ,  $b$ -quark
- Extract coupling deviations from SM prediction from per-channel signal rates
- Assumptions:  $m_H = 125 \text{ GeV}/c^2$ , negligible width,  $CP\ 0^+$ , no invisible decay

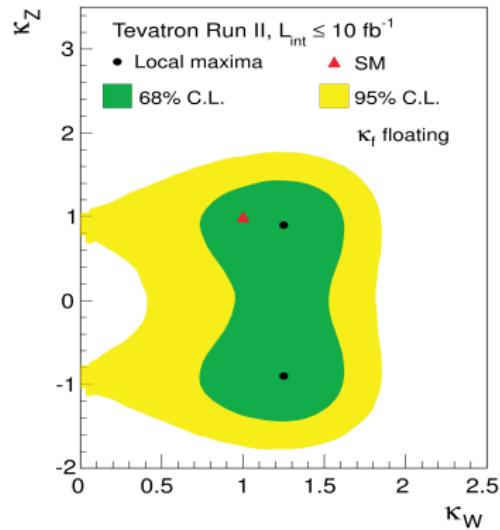
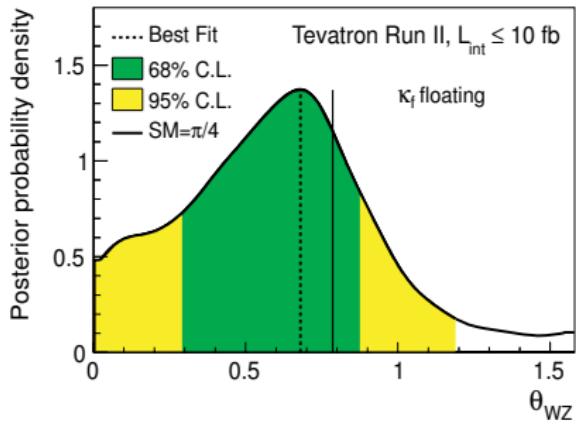
- $\kappa_f$  fermion couplings scale
- $\kappa_V$  boson coupling scale (if  $\kappa_Z \equiv \kappa_W$ )
- Examples:
  - $\Gamma_{b\bar{b}} \propto \kappa_f^2$ ,  $\Gamma_{\tau\bar{\tau}} \propto \kappa_f^2$ ,  $\Gamma_{ZZ} \propto \kappa_V^2$
  - $\Gamma_{WW} \propto R\kappa_V^2$  (with  $R = \kappa_W/\kappa_Z$ )
- Preserve unitary in BR:  
es.  $\Gamma_{\gamma\gamma} \propto (1.28\kappa_f - 0.281\kappa_V)^2$
- Study of coupling multiplicative parameters with 1-dim and 2-dim (*shown*) Bayesian posteriors



# Vector Boson Couplings: $\kappa_W$ vs $\kappa_Z$

Separate measurement of  $\kappa_Z$  vs  $\kappa_W$

- $\kappa_f$  is marginalized
- 95% C.L. exclusion of no-Higgs hypothesis:  $(\kappa_Z, \kappa_W) = (0, 0)$
- 2-dim best fit:  
 $\Rightarrow (\kappa_Z, \kappa_W) = (1.25, \pm 0.90)$



Test of  $SU(2)$  custodial symmetry:

- by measuring  $\lambda_{WZ} = \kappa_W / \kappa_Z$
- $\theta_{WZ} = \tan^{-1}(\kappa_Z / \kappa_W) = \tan^{-1}(1 / \lambda_{WZ})$
- $\theta_{WZ} = 0.68^{+0.21}_{-0.41} \Rightarrow \lambda_{WZ} = 1.24^{+2.34}_{-0.42}$

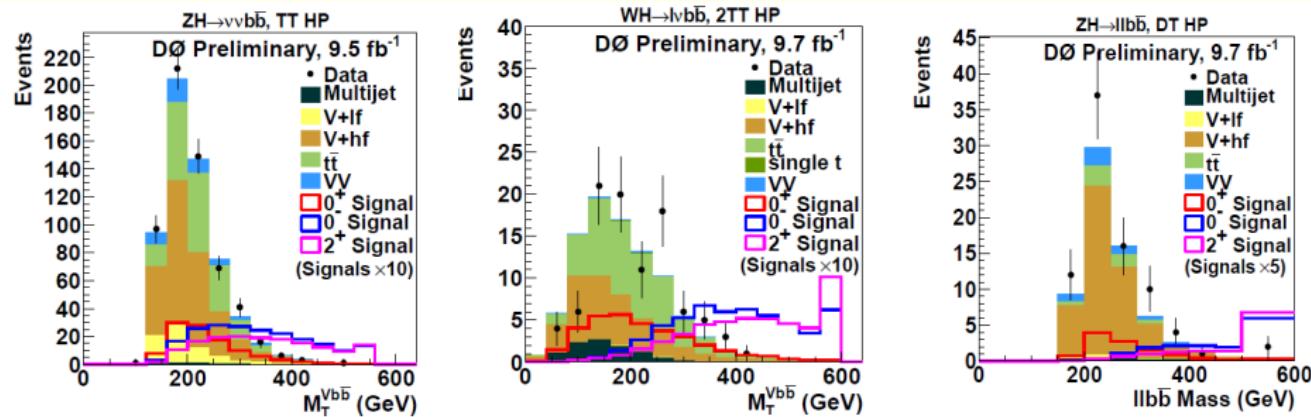


# Additional Properties: Spin and Parity

- $VH$  production processes differ depending on  $J^P$  assignment
- Kinematic differences from behaviors at production threshold, if  $\beta = 2p/\sqrt{s}$ :
- $0^+$ : S-wave production,  $\sigma \propto \beta$  near threshold
- $0^-$ : P-wave production,  $\sigma \propto \beta^3$  near threshold
- $2^+$ : D-wave dominates for graviton-like coupling,  $\sigma \propto \beta^5$

cf. Ellis, et al., JHEP 1211, 134 (2012),  
and Miller, et al., PLB 505, 149, (2001)

Probe Higgs  $J^P$  with  $VH$  total mass variables  $\Rightarrow$  background discrimination better than for  $0^+$ :

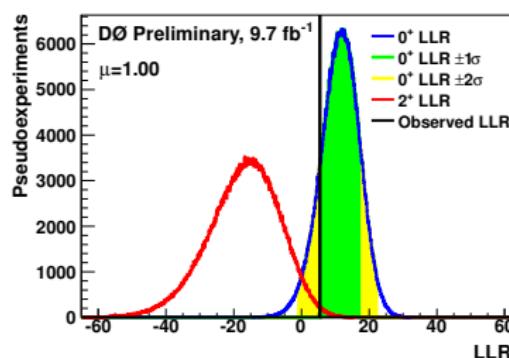
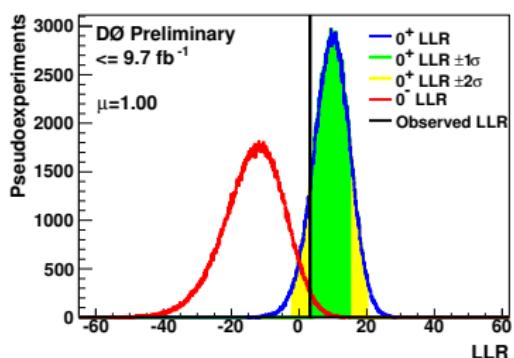


- $2^+$  result Summer 2013: [D0 Note 6387](#)
- $0^-$  recent result (Autumn 2013): [D0 Note 6406](#)



# Results of Spin and Parity Analysis

- Known  $m_H$  used in analysis optimization:  
⇒ selection of High/Low purity regions in reconstructed mass
- LLR test statistics used to distinguish two hypothesis with  $CL_s$ :  
⇒ H1 (Test): background plus  $0^-$  or  $2^+$  Higgs signal  
⇒ H0 (Null): background plus  $0^+$  Higgs signal
- Two scenarios: SM like  $\sigma_{VH} \times BR(b\bar{b})$  (shown), or D0 measured rate ( $\mu = 1.23$ )

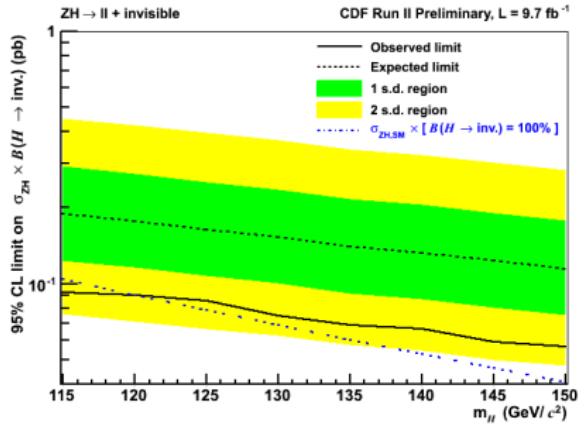
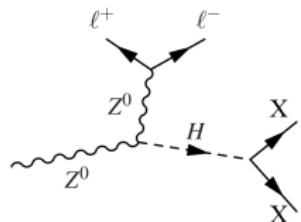


## Exclusions results:

- $0^-$  model excluded at  $> 97.9\% \text{ C.L.}$  ( $2.3\sigma \text{ obs}, 3.1\sigma \text{ exp}$ )
- $2^+$  model excluded at  $> 99.9\% \text{ C.L.}$  ( $2.4\sigma \text{ obs}, 3.2\sigma \text{ exp}$ )
- Very good sensitivity but model dependent assumptions

# Invisible Higgs

- New CDF analysis testing exotic Higgs models: [CDF Note 11068](#)
- First measurement at the Tevatron probing  $\sigma_{ZH} \times BR(H \rightarrow \text{invisible})$
- If kinematically accessible, decays to heavy unknown and weakly interacting particles are likely because of Yukawa coupling ( $\propto m$ ) to Higgs
- $ZH \rightarrow \ell\ell + \cancel{E}_T$ :  $82 < M_{\ell\ell} < 100 \text{ GeV}/c^2$ , clean signature
- Bayesian 95% C.L. exclude 100%  $BR(H \rightarrow \text{invisible})$  for  $m_H < 120 \text{ GeV}/c^2$



# Summary and Prospects

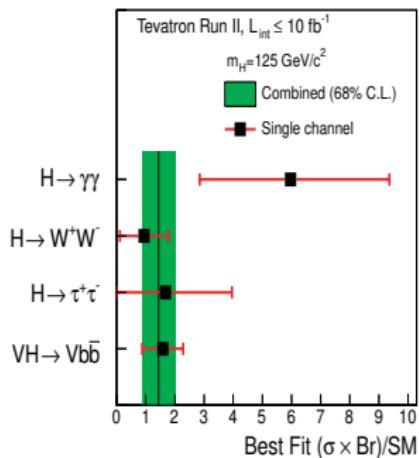
## Summary of Tevatron Run II Higgs studies:

- High and low Higgs mass analysis channels based on full dataset completed and published
- Data show a consistent picture of the SM Higgs:
  - ⇒ p-value  $3.0\sigma$  (local) at  $m_H = 125 \text{ GeV}/c^2$
  - ⇒  $\mu = \sigma_{obs}/\sigma_{SM} = 1.44^{+0.59}_{-0.56}$  at  $m_H = 125 \text{ GeV}/c^2$

## Recent results and work in progress:

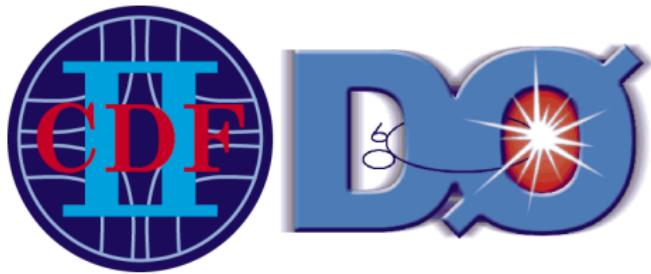
- $VH \rightarrow b\bar{b}$  datasets re-analyzed by D0 collaboration extracting spin and CP measurements:
  - ⇒  $J^P = 0^+$  nature of the new particle are favored
  - ⇒  $J^P = 2^+, 0^-$  models rejected at  $> 97\%$  C.L.
  - ⇒ Tevatron combination is in progress
- Exotic Higgs properties:
  - ⇒ new analysis  $H \rightarrow \text{invisible}$

$(\sigma \times BR)/SM$  for decay channel:



Tevatron analyses still provide good sensitivity to  $H \rightarrow b\bar{b}$  final state and Higgs properties studies are often complementary to LHC

# Thanks for Your Attention



# Back Up Slides

# All Channels and Analysis Details References

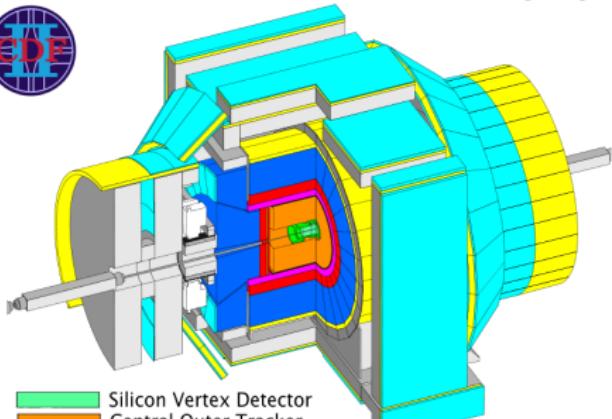
Channel		Luminosity (fb <sup>-1</sup> )	$m_H$ range (GeV/c <sup>2</sup> )
$WH \rightarrow \ell\nu b\bar{b}$ 2-jet channels $4 \times (5b\text{-tag categories})$		9.45	90–150
$WH \rightarrow \ell\nu b\bar{b}$ 3-jet channels $3 \times (2b\text{-tag categories})$		9.45	90–150
$ZH \rightarrow \nu\bar{\nu} b\bar{b}$ (3b-tag categories)		9.45	90–150
$ZH \rightarrow \ell^+\ell^- b\bar{b}$ 2-jet channels $2 \times (4b\text{-tag categories})$	$H \rightarrow b\bar{b}$	9.45	90–150
$ZH \rightarrow \ell^+\ell^- b\bar{b}$ 3-jet channels $2 \times (4b\text{-tag categories})$		9.45	90–150
$WH + ZH \rightarrow jj b\bar{b}$ (2b-tag categories)		9.45	100–150
$t\bar{t}H \rightarrow W^+ bW^- b\bar{b}\bar{b}$ (4 jets, 5 jets, $\geq 6$ jets) $\times (5b\text{-tag categories})$		9.45	100–150
$H \rightarrow W^+W^-$ $2 \times (0\text{ jets}) + 2 \times (1\text{ jet}) + 1 \times (\geq 2\text{ jets}) + 1 \times (\text{low-}m_{\ell\ell})$		9.7	110–200
$H \rightarrow W^+W^-$ ( $e\text{-}\tau_{\text{had}}$ ) + ( $\mu\text{-}\tau_{\text{had}}$ )		9.7	130–200
$WH \rightarrow WW^+W^-$ (same-sign leptons) + (trileptons)	$H \rightarrow W^+W^-$	9.7	110–200
$WH \rightarrow WW^+W^-$ (trileptons with $1\tau_{\text{had}}$ )		9.7	130–200
$ZH \rightarrow ZW^+W^-$ (trileptons with 1 jet, $\geq 2$ jets)		9.7	110–200
$H \rightarrow \tau^+\tau^-$ (1 jet) + ( $\geq 2$ jets)	$H \rightarrow \tau^+\tau^-$	6.0	100–150
$H \rightarrow \gamma\gamma$ $1 \times (0\text{ jet}) + 1 \times (\geq 1\text{ jet}) + 3 \times (\text{all jets})$	$H \rightarrow \gamma\gamma$	10.0	100–150
$H \rightarrow ZZ$ (four leptons)	$H \rightarrow ZZ$	9.7	120–200



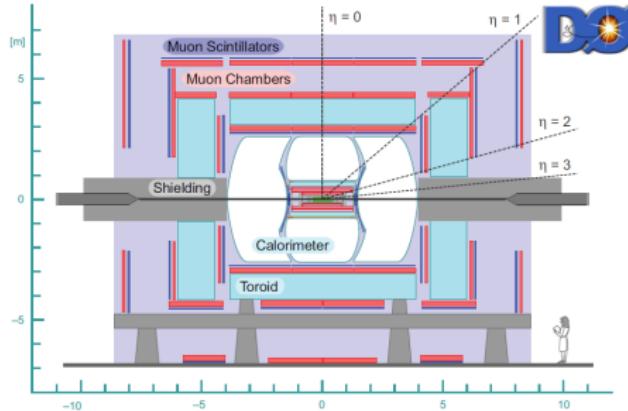
# The CDF and D0 Experiments



## Multipurpose detectors:



- █ Silicon Vertex Detector
- █ Central Outer Tracker
- █ 1.4 T Superconducting Solenoid
- █ EM Calorimeter
- █ Hadron Calorimeter
- █ Muon Counters/Chambers



Silicon ( $|\eta| < 2.5$ ,  $r \simeq 20$  cm)  
 Drift cell ( $|\eta| < 1.1$ ,  $r \simeq 130$  cm)

Pb/Fe/Scintillators ( $|\eta| < 3.6$ )

Drift/Scintillators ( $|\eta| < 1.5$ )

**Inner Tracker  
Outer Tracker**

**Calorimeters**

**Muon Chambers**

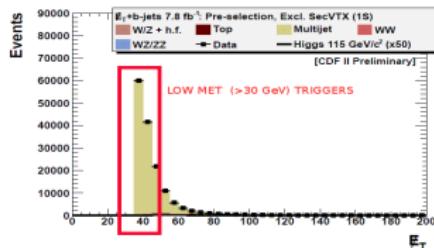
Silicon ( $|\eta| < 3.0$ ,  $r \simeq 10$  cm)  
 Fiber ( $|\eta| < 1.7$ ,  $r \simeq 50$  cm)

LAr/U ( $|\eta| < 4.0$ )

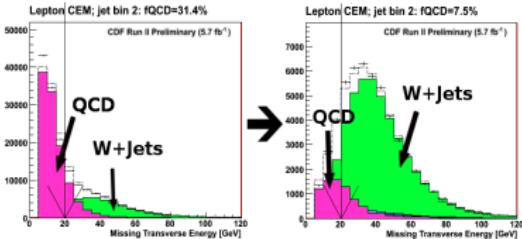
Drift/Scintillators  $|\eta| < 2.0$

# Analysis Improvement Examples

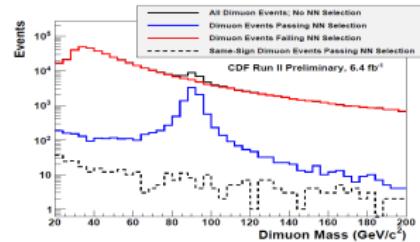
Low trigger thresholds (multi-dim. turn-on model):



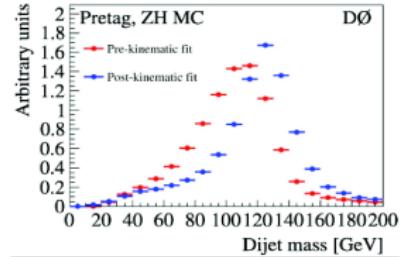
Variety of MJ-rejection techniques (here cut on SVM):



Lepton ID with NN selection:

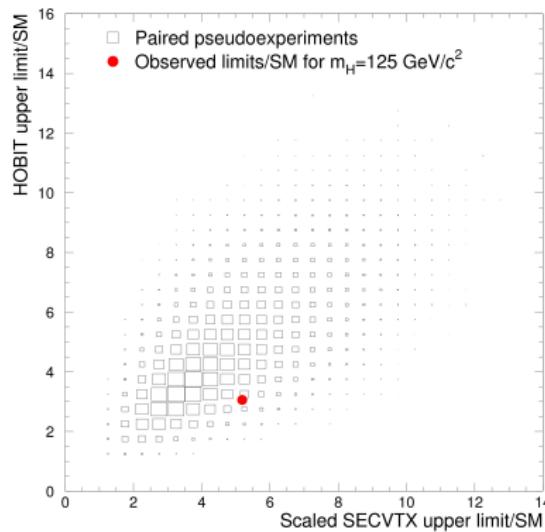


$Z \rightarrow \ell\ell$  kinematic fit to improve  $M_{jj}$  resolution:



# CDF $ZH \rightarrow \nu\nu + HF$ Update

- 2012 result documented in Phys. Rev. Lett. 109, 111805 (2012), Updated 2013 result documented in Phys. Rev. D 87, 052008 (2013)
- Different b-tagging and, therefore, different signal region categorization: new result more sensitive but with lower observed limit
- Fluctuation possible with 7% probability tested with P.E.

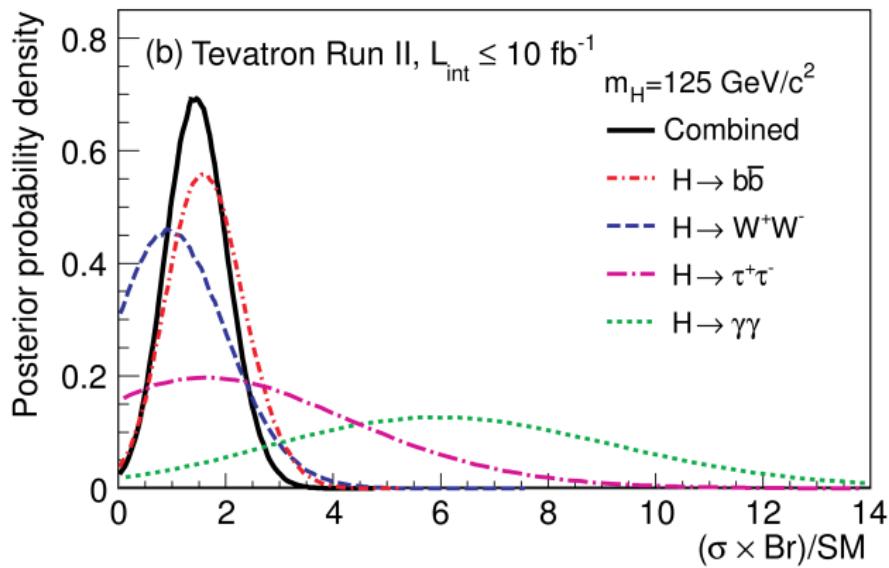


Two-sided p-value by calculating the conditional probability of obtaining a HOBIT result that is as or more discrepant than what we observe, given the S-J reanalysis observed limit

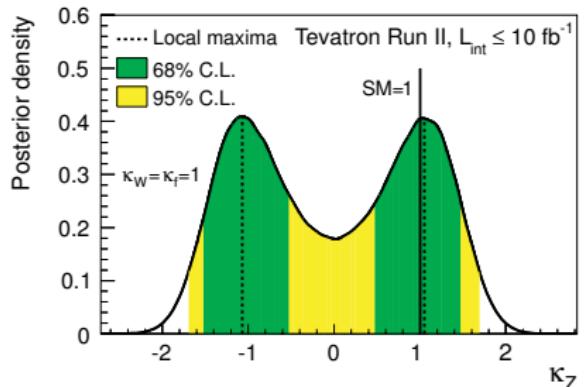
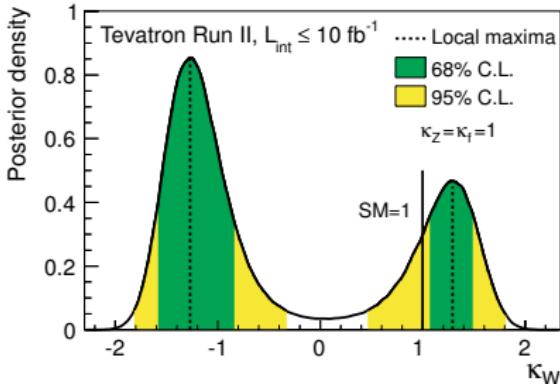
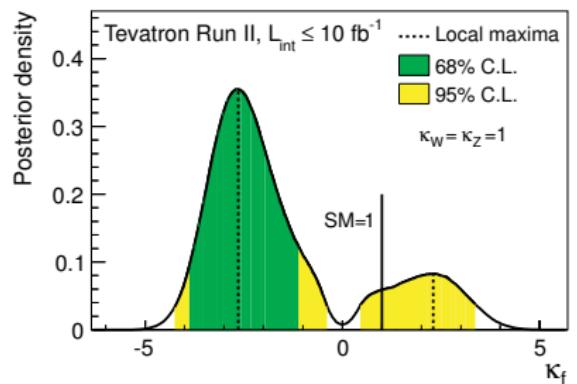
# SM Higgs Compatibility Between Final States



$(\sigma_H \times BR)/SM$  in different final states:



# 1-Dim $\kappa_f$ , $\kappa_W$ , and $\kappa_Z$



# Spin Exclusions Using D0 Measured SM Higgs Signal Strength

